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(21) Application No 8120213
(22) Date of filing 30 Jun 1981
(30) Priority data
(31) PCT/US 80/00925
(32) 24 Jul 1980
(33) United States of America (US)

(43) Application published
17 Feb 1982

(51) INT CL³
G01V 1/38

(52) Domestic classification
G1G 1G2 3P 4A5 7P MC

(56) Documents cited
GB 1193507

(58) Field of search
G1G

(71) Applicants
Fairfield Industries Inc.,
10052 Harwin Dr.
Houston,
Texas 77036,
United States of America.

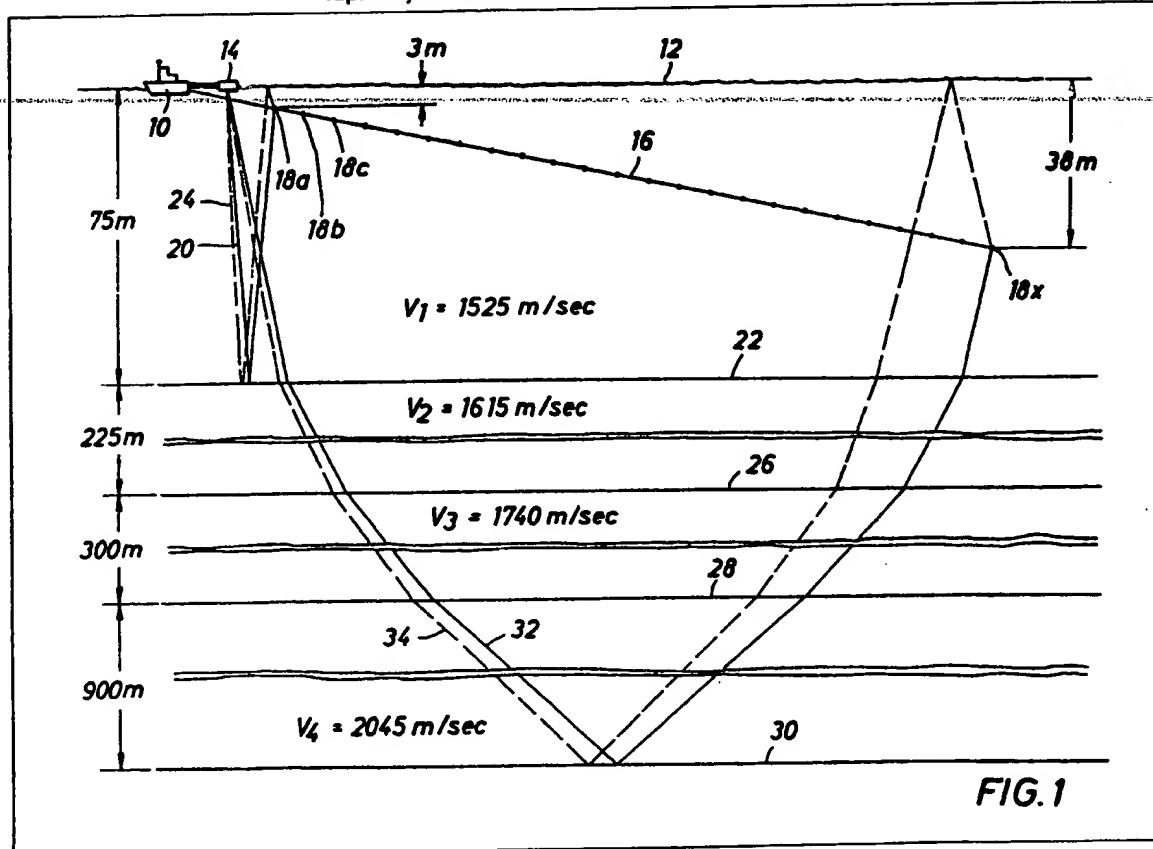
(72) Inventors
Clifford H. Ray,
Neil A. Moore.

(74) Agents
Forrester, Ketley & Co.,
Forrester House,
52 Bounds Green Road,
London N11 2EY.

(54) A high resolution marine seismic
stratigraphic system

(57) A high resolution seismic stratig-
raphic system and method for collect-

ing and processing seismic data are described. The system comprises a movable seismic source (14) for introducing an acoustic pulse into a body of water covering part of the Earth's surface, for example a lake or sea and detecting means movable synchronously with the source by a towing vessel (10) comprising a cable (16) arranged below the water surface (12) at an angle thereto having a plurality of detectors in the form of hydrophone arrays (18a to 18x) spaced along the length thereof for detecting primary and ghost reflection pulses produced by reflection of the source pulse from reflection interfaces on or beneath the lake or sea bed. The primary reflection pulses detected are time-aligned and stacked whilst the ghost reflection pulses are phase-reversed time-aligned, stacked and time-shifted to coincide with the time-aligned primary pulses. A combined primary and ghost reflection pulse stack is then produced.



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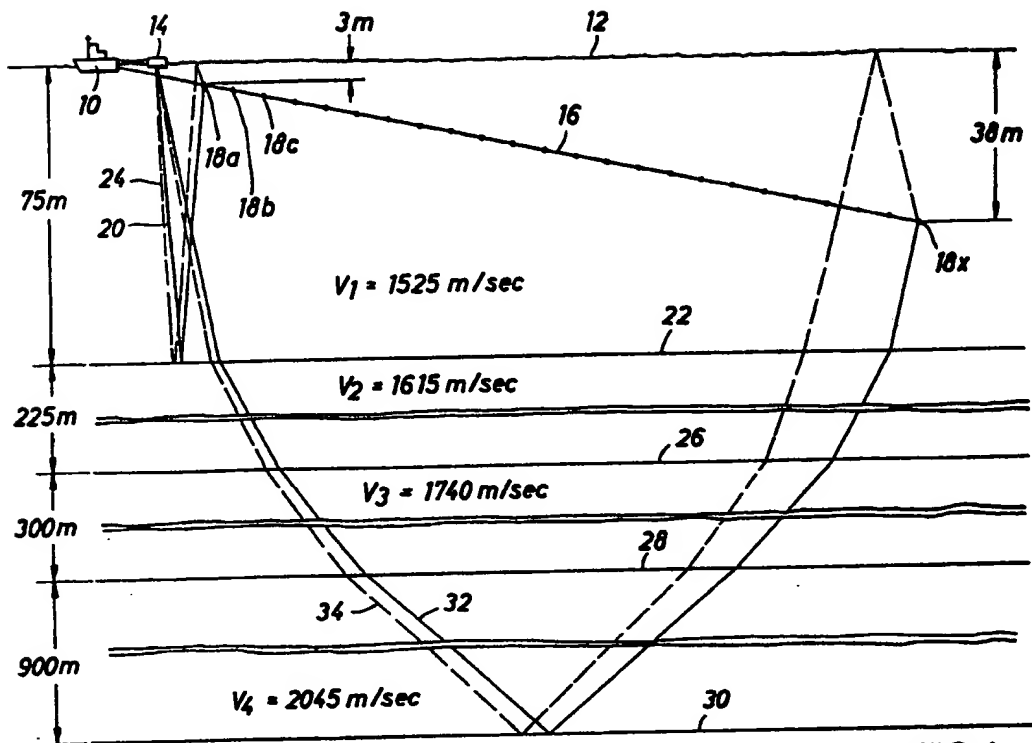


FIG. 1

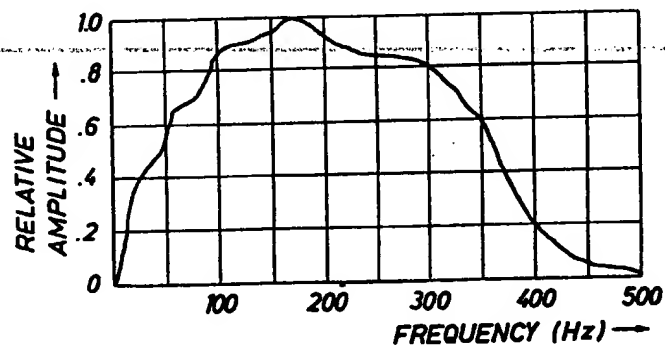


FIG. 2

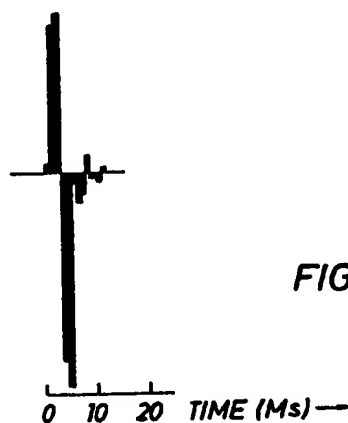


FIG. 3

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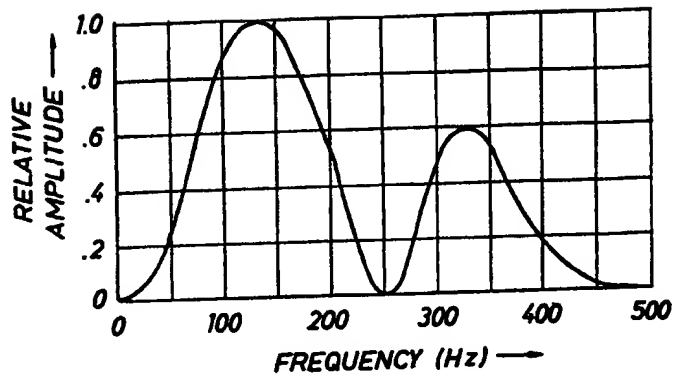


FIG. 4

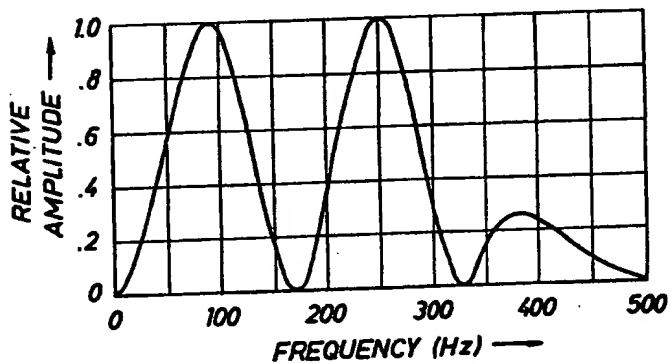


FIG. 5

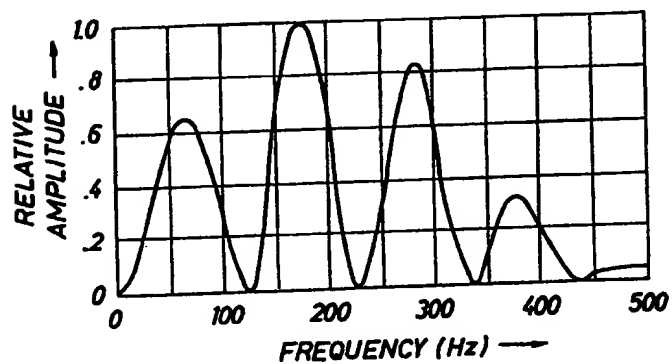


FIG. 6

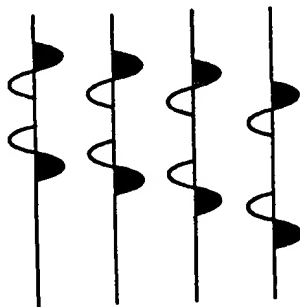


FIG. 7

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FIG. 8

FIG. 9

FIG. 10

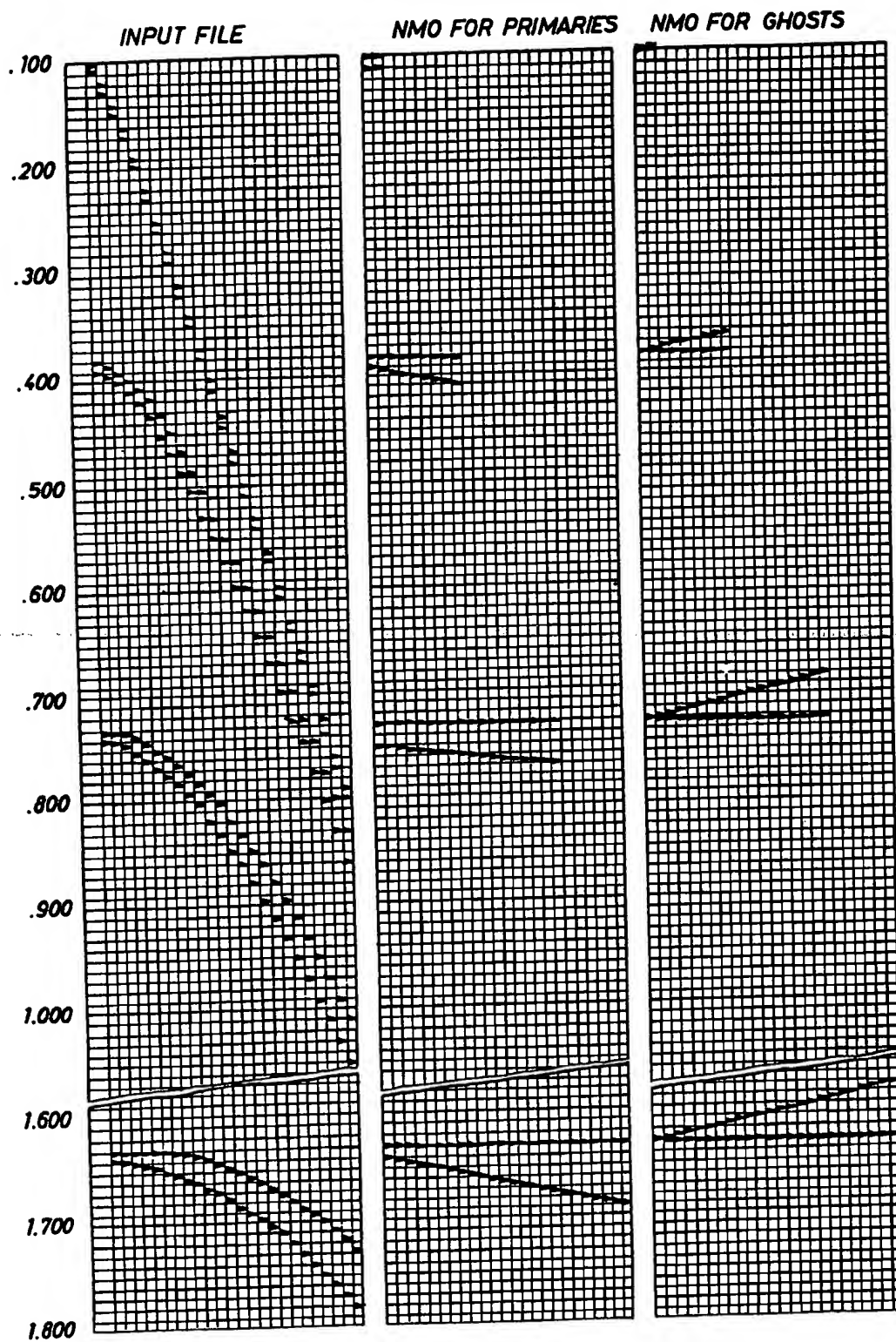
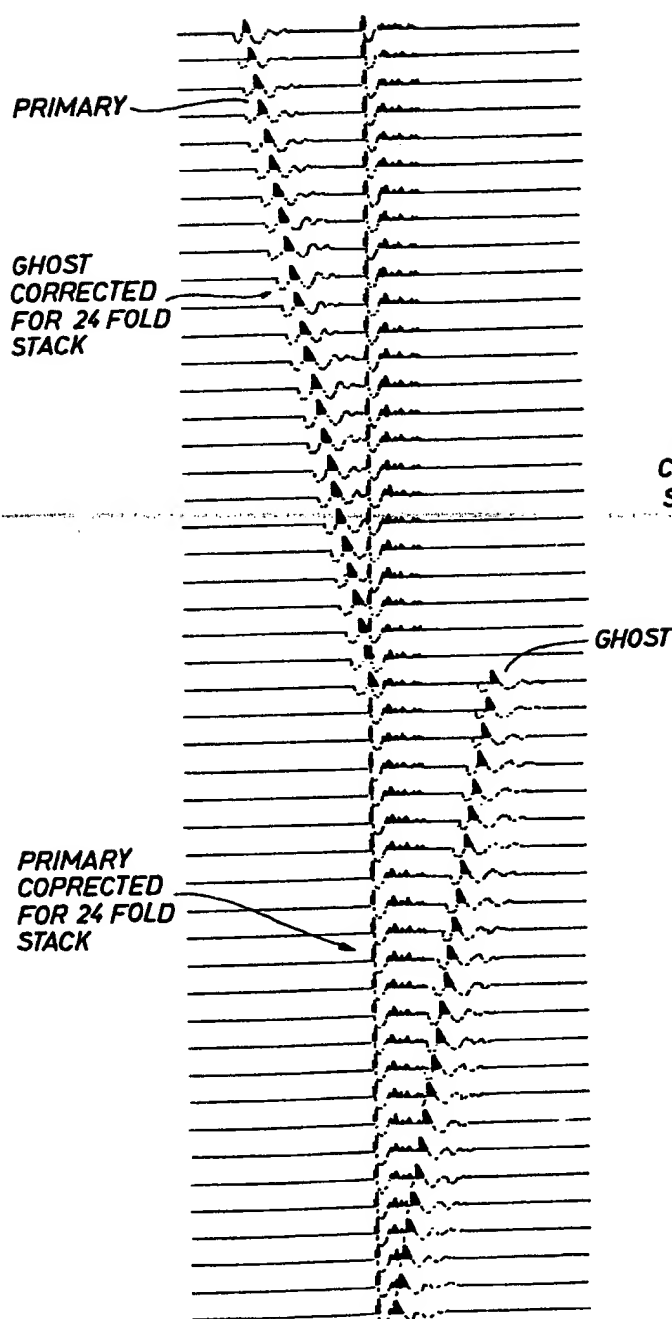


FIG. 11



A. PRIMARY STACK

B. GHOST STACK

C. COMBINED STACK

FIG. 12

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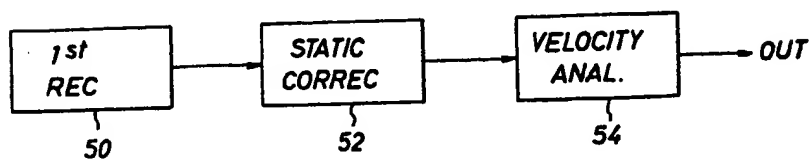
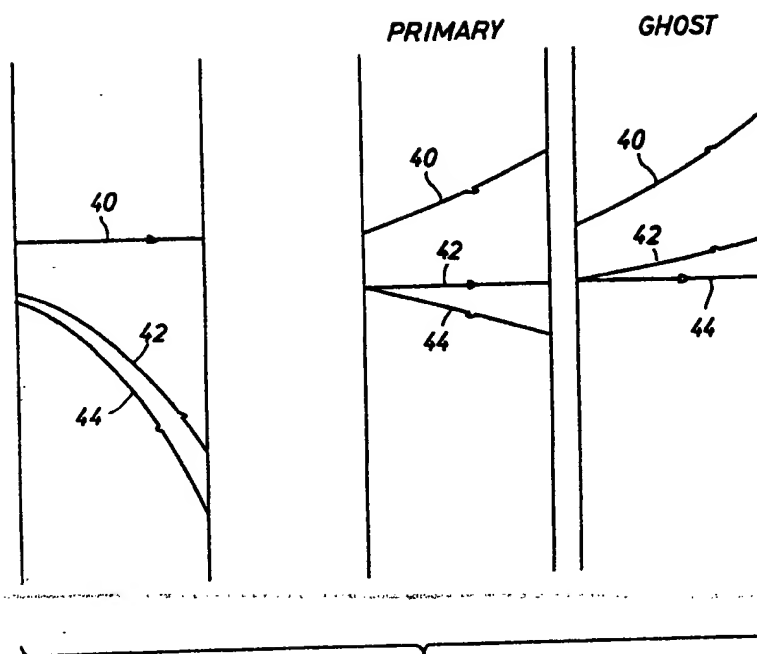
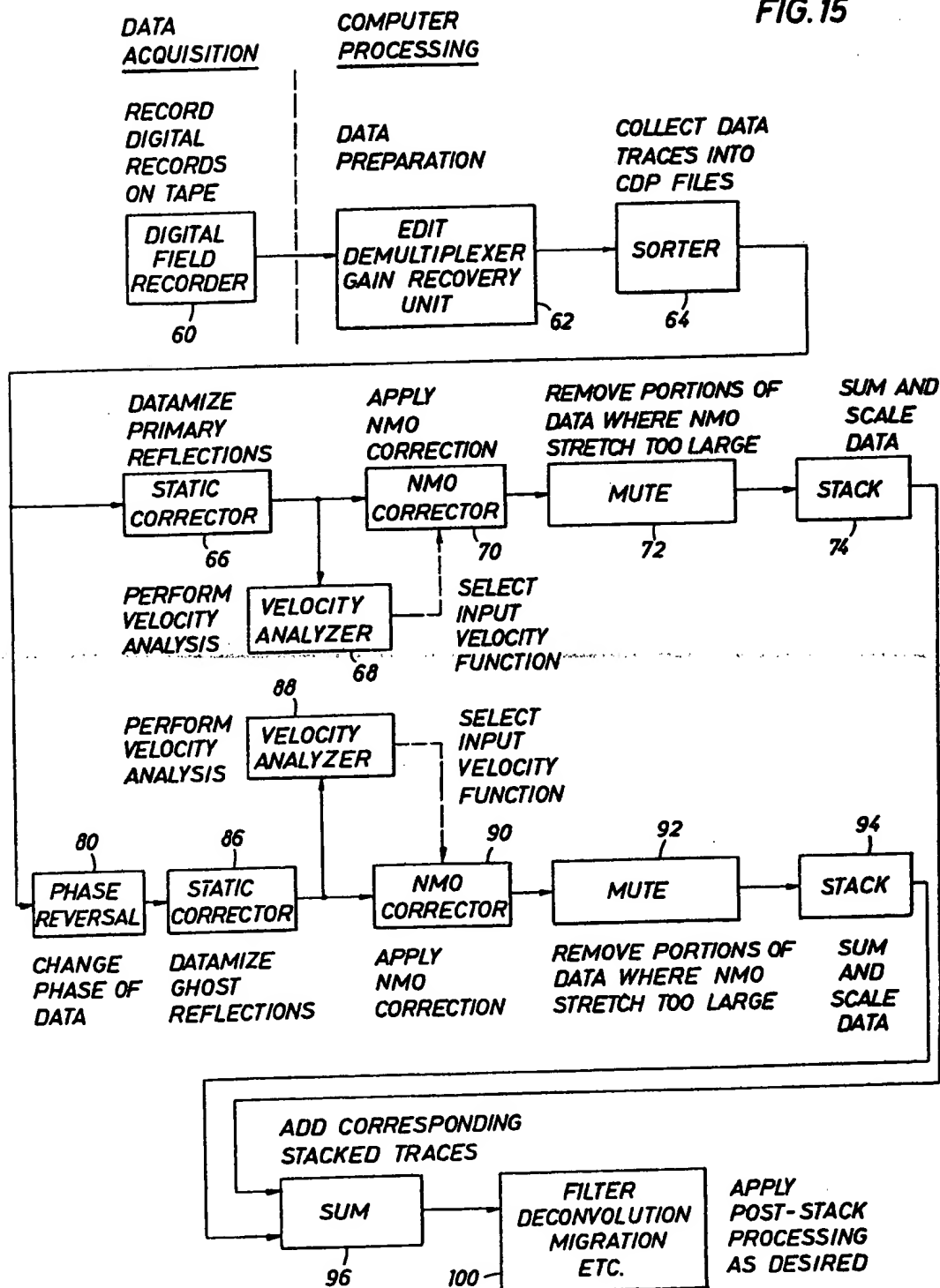


FIG. 15



SPECIFICATION

High resolution, marine seismic stratigraphic system

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This invention pertains to seismic stratigraphic systems and more particularly to an improved high resolution marine seismic stratigraphic system.

In a typical marine seismic system, data is collected by means of a vessel equipped with both an acoustic energy source, usually provided on a submerged carrier towed by the vessel with certain control apparatus therefor being located on the vessel, and an acoustic detector array, usually in the form of a complex cable also towed by the vessel. Such a detector cable is typically towed at a shallow depth beneath the water surface behind the vessel and is best characterized as a streamer or an extended cable including a plurality of seismic detectors or hydrophones. It is also usual for the detectors to be spaced along the streamer in multiple arrays, rather than singly. The towed streamer is ideally neutrally buoyant and seeks a uniform depth beneath the surface of the water, usually in the vicinity of from one to three metres. The primary reason that the streamer is towed below the water surface is to avoid, insofar as possible, the effects of surface wave action or turbulence.

The return pulses detected by the hydrophone arrays are a result of the acoustic pulses from the source being reflected from the various subsurface seismic interfaces. One such interface is the interface between the water and the land, or in other words, the lake or ocean bottom. Other interfaces occur wherever there is a lithological variation or change. Knowledge of such interfaces or reflecting surfaces is extremely valuable in evaluating the presence of hydrocarbon deposits and the like.

The acoustic return data gathered using such a streamer of hydrophone arrays is subjected to several natural phenomena which interfere with a clear interpretation of the data collected, unless avoided or minimized and/or corrected. One of these phenomena is surface noise. It is well-known that a hydrophone located at or near the water surface will pick up surface wave motion. Therefore, it has been found convenient to locate the hydrophone detectors below the water surface, typically of the order of one to three metres (although such below-surface location introduces ghost returns, which are discussed below).

Another recognized phenomenon that must be considered before the collected data is clearly interpretable is the phenomenon known as correcting to a common depth point (CDP) file. Data may ideally be gathered at a common depth point; however, as will be explained, it is not normally practical to do so, particularly in a marine configuration setting. But, for an understanding of the concept, consider a horizontal reflecting interface with a point thereon as the "CDP". Along a parallel "datum" line above the interface, and to the side of a normal drawn to the CDP, are evenly spaced detectors. (Actually, there is normally a detector array, but for discussion here in "detector" is used to signify an associated array of

group of individual detectors). Along the datum line and to the other side of the normal drawn to the CDP, are equally evenly spaced sources. A first data trace would be the result of a pulse from the closest source being reflected off the interface and received at the closest detector. A second data trace would be the result of a pulse from the next closest source being reflected off the interface and received at the next closest detector. Similarly, data traces developed from successive sources to successive detectors, each resulting from a reflection off the interface at the CDP, would develop a "common depth point file".

However, there is normally only one source in a typical marine seismic system, which source is towed at a predetermined rate. Assuming that the detectors were stationary and evenly spaced, when the source was at a position corresponding to the first source in the above example, then the second, and so forth, an ideal CDP file could be developed. In the normal system, however, the detectors are not stationary, but are towed in conjunction with or at the same rate as the source. Therefore, it may be seen that a two-trace, or "two-fold" common depth point file is developed when the source is pulsed at an initial position and then pulsed again when it and the detector cable have been towed together one-half of the detector spacing distance, the first pulse being detected by the first detector and the second pulse being detected by the second detector. The process can then be repeated for as many detectors as there are on the cable for a full-fold CDP file.

Of course, data is not actually collected in the field in the manner just described. In practice, a source pulse is detected at all of the detectors, but not from a common depth point. Then at a second location of the source, which normally would be at a distance from the place where the source was first pulsed, the source is again pulsed and the return pulse detected at each of the detectors, again following reflection from different depth points. From the individual field recordings, data associated with a common depth point is selected and is built up in what is truly a common "CDP" file". Hence, interpretation is not from the field recordings but from the CDP files.

Because the travel time for a pulse from the source to the reflecting interface to the detector is longer for the second detected trace than for the first detected trace in a CDP file, and for the third detected trace than for the second detected trace, and so forth, a correction is necessary for the subsequent data traces or events to position them in time with the first data trace or event. Such correction is referred to as the normal moveout (NMO) correction. Factors involved in making such correction, which is different for each detector event resulting from a successively spaced detector, are well-known in the art and are explained, for example, in *Geophysics*, a publication of the Society of Exploration Geophysicists, Vol 27, No. 6, published in 1962 at page 927, in an article entitled "Common Reflection Point Horizontal Data Stacking Techniques", W.H. Mayne.

Distortion caused by cable drop is usually just tolerated. The buoyancy of a cable can be modified to achieve an adjusted location that is more closely

parallel to the surface when there is an appreciable deviation from the horizontal. It is also possible to correct droop-distorted data by determining the amount of droop by measurement and then correcting the data collected to a surface "datum" line, such as for correcting for uneven land surface swells in a land seismic system. This correction is usually done even when the cable is approximately parallel to the water surface anyway.

Unwanted noise, other than mere static or random noise, is a frustrating phenomenon that is usually just tolerated. Such noise can arise out of the vertical plane or profile of the cable and may result from a source not related to the seismic source employed in the system or from a reflection of the seismic source at other than an lithological interface barrier from below. For example, a noise progressing underwater at a sideways angle to the cable constitutes such noise.

Perhaps the most disturbing and hardest to correct of all external effects however, has been the effect introduced by ghost reflection pulses. A pulse signal from the source progresses downwardly through the water until it is reflected upwardly by the interface at the bottom of the water to be received by the hydrophone. In addition, however, there is a reflection pulse that continues to the surface and is then reflected downward by the water-to-air interface to be received at the hydrophone at a slightly later time than the direct or primary reflection pulse. This reflection pulse is referred to as the ghost reflection. The combination of the primary reflection pulse and the ghost reflection pulse produces a pulse having a distorted shape compared to the source pulse. For example, assuming a source pulse having a broad frequency spectrum, the relative amplitude in the frequency domain being approximately centred about a mid frequency and decreasing gradually therefrom over about three octaves, the arrival of the primary reflection pulse and the associated ghost reflection pulse at a detector will produce a multiply peaked response in the frequency domain of the source pulse. The effect of the ghost reflection pulse on the primary reflection pulse can be analyzed to determine at which frequencies within the spectrum there is interference cancellation and at which frequencies there is interference augmentation or reinforcement, resulting in amplitude distortion over the entire frequency range. At each interface, a primary reflection pulse and a ghost reflection pulse are produced. The distortion in the shape of the frequency domain response depends on the separation of the ghost reflection pulse from the primary reflection pulse. Thus, the further the two are apart, the greater the number of peaks and thus the number of notches therebetween in the response produced.

Since the results of the interaction of a ghost reflection pulse on the associated primary reflection pulse is subject to analysis, it is common to design an inverse electronic filter to correct for the amplitude distortion which results. In a very real sense, when compared to an ideal undistorted response, the actual reflected responses can be viewed as having been subjected to an unwanted analog

filter caused by the interface reflections and the mediums through which the reflections travel. Therefore, the purpose of inverse electronic filters employed in the prior art systems is to restore the reflected event response to appear as the source pulse, which it may be remembered in the above example, was shaped to have a smooth single peak in the frequency domain, the amplitude of which decreases gradually on either side of a centre frequency for about three octaves.

It is apparent that such a compensating filter amplifies frequencies close to a notch greatly in order to restore the lost resolution. In doing so, it is also readily apparent that such an inverse filter introduces noise and thereby causes a decrease in the signal-to-noise ratio. The presence of an inverse filter also has the effect of reducing penetration of the effective source transmission and reflection reception since noise amplification is inherent, and, hence, unavoidable.

For combination primary and ghost reflection pulse responses developed at detectors progressively further from the source than the near detector, as mentioned above, the Fourier transform response caused by the ghosting phenomenon creates so-called "trace depth notches", at slightly different locations from the notch of the response at the first detector. It should be noted, therefore, that the ghosting phenomenon introduces a phase as well as an amplitude distortion. Hence, to correct for both amplitude and phase distortion of these trace depth notches in these responses, it has been a practice in the prior art, at the appropriate phase positions involved (in other words, at the slightly different notch locations for the responses associated with each detector), to insert inverse filtering during the data processing stage. Such processing introduces compensating amplification at the notch locations and compensating attenuation for the sharp sides of the response on either side of the notches.

According to one aspect of the present invention there is provided a system for collecting and processing seismic data comprising: a movable seismic source for introducing an acoustic pulse into a body of water covering part of the Earth's surface; detecting means movable synchronously with the source by towing means and comprising a cable arranged below the water surface at an angle thereto having a plurality of detectors spaced along the length thereof, each of the detectors being provided to detect both primary and ghost reflection pulses produced by reflection of the source pulse from a reflection interface or interfaces at or within the part of the Earth's surface substantially beneath the body of water; and primary reflection pulse correction means for time-aligning the primary reflection pulses and stacking the time-aligning pulses to emphasize the primary reflection pulses with respect to the ghost reflection pulses.

According to a second aspect of the present invention there is provided a method for collecting and processing seismic data, comprising: introducing an acoustic pulse having a broad frequency spectrum into a body of water covering part of the Earth's surface; detecting the primary and ghost

reflection pulses reflected from reflection interfaces at or within the part of the Earth's surface substantially beneath the body of water at a plurality of detector locations, the first detector location being
 5 sufficiently beneath the surface of the water to be substantially free of surface interference and successive detector locations being positioned increasingly deeper beneath the water surface; time-aligning the
 - detected primary reflection pulses; and stacking the
 10 time-aligned detected reflection pulses to emphasize the primary reflection pulses with respect to the ghost reflection pulses.

A preferred embodiment of the invention provides a high resolution marine seismic stratigraphic system comprising a broad frequency spectrum source
 15 for introducing a pulse into the water, the source being towed by a vessel which also tows a detector cable. The cable or streamer includes a plurality, preferably twenty-four, of hydrophones or hydrophone detector arrays (often referred to herein as "detectors"), the detector located nearest to the
 20 vessel being at a depth of about three metres beneath the water surface. The cable is buoyantly controlled to slope at a relatively constant angle, preferably of a little less than two degrees and approximately 1.75 degrees, so that the detector
 25 furthest from the vessel is at a depth of about 38 metres. A primary reflection pulse from each seismic interface and a corresponding ghost reflection pulse
 30 is received by each detector and recorded on an appropriate field recorder in conventional fashion. For each reflecting interface, because of the slope of the cable, the primary and ghost reflection pulses become further and further spaced-apart in time as
 35 the distance of the detector source increases.

After recording, the data are computer processed. Normal data processing operations applied to the recorded data include such things as demultiplexing, gain recovery, and sorting into common depth point
 40 files. Static time shifts are applied to correct the arrival times of reflection pulses at the respective detectors to the times at which a common datum plane, usually the surface of the water, would have been reached by the pulses. Then for each interface,
 45 the velocity for the primary reflection pulses is determined, an NMO correction is applied, and the primary reflection pulses are time aligned and stacked in the time domain, thereby producing an enhanced or emphasized primary reflection pulse
 - stack while not enhancing the individual ghost
 50 reflection pulses since they are not time-aligned.

Static corrections are also applied to correct the ghost reflection pulses to the common datum plane and the phase of the ghost reflection pulses is reversed.
 55 The velocity for the ghost reflections pulse which may be a little different from that of the primary reflection pulses as the water path for the ghost reflection pulses may be slightly different than for the corresponding primary reflection path is then
 60 determined, the NMO correction applied, and the ghost reflections time aligned and stacked in the time domain, thereby producing an augmented ghost stack while not enhancing the primary stack since they are not time aligned. The two stacks are
 65 then added to produce an effective 48-fold stack,

instead of only a 24-fold stack as with the prior art systems. After completion of the above process, there is no amplitude or phase distortion produced by the ghosting phenomenon and there is a complete avoidance of the use of any inverse notch filter.
 70 Hence, with respect to prior art systems, the resolution is increased, the penetration is increased and the directivity or focus is enhanced (directed noise other than in the vertical plane being relatively
 75 non-enhanced and even cancelled to some extent in the above procedure).

In order that the invention may be more readily understood, an embodiment thereof will now be described, by way of example, with reference to the
 80 accompanying drawings, in which:

Figure 1 is a schematic illustration of a marine seismic stratigraphic system embodying the present invention;

Figure 2 is a diagram of the frequency spectrum of the source pulse used in the system of *Figure 1*;

Figure 3 is a digital time domain diagram of the source pulse shown in *Figure 2*;

Figure 4 is a diagram of the frequency spectrum of the combined primary and ghost reflection signals
 90 from a deep interface or horizon received at a first detector in a cable of the system of *Figure 1*;

Figure 5 is a diagram of the frequency spectrum of the combined primary and ghost reflection signals from the deep reflecting interface received at a
 95 second detector in the cable of the system of *Figure 1*;

Figure 6 is a diagram of the frequency spectrum of the combined primary and ghost reflection signals from the deep reflecting interface received at a third
 100 detector in the cable of the system of *Figure 1*;

Figure 7 is an expanded example of a time domain diagram illustrating for explanation purposes the shape and shading of the variable area traces shown
 in *Figures 8, 9 and 10*;

Figure 8 is a diagram of a common depth point file in the time domain of primary and ghost reflections from progressively deeper interfaces or horizons at each of twenty-four detectors located along the
 105 cable of the system of *Figure 1* without static corrections;

Figure 9 is a diagram of static and NMO corrected data in the time domain of the primary and ghost reflections shown in *Figure 8*, the primary reflections being time aligned and the data being muted to
 115 eliminate the effects of NMO stretch;

Figure 10 is a diagram of static and NMO corrected data in the time domain of the ghost reflections shown in *Figure 8*, the reflections having been phase reversed, the ghost reflections being time aligned
 120 and the data being muted to eliminate the effects of NMO stretch;

Figure 11 is a diagram showing the effects of data alignment by a system embodying the present invention following data gathering in accordance
 125 with a method embodying the present invention, but prior to stacking;

Figure 12 is a diagram of stacking enhancement with respect to the primary reflections, the ghost reflections and the combination of both;

130 *Figure 13* is a diagram of the effect of the

cancellation of noise not directed in the vertical plane, by a method embodying the present invention;

Figure 14 is a block diagram of components of the system of Figure 1 used for velocity determination for data collected along a discrete lithological path; and

Figure 15 is a block diagram of components of the system of Figure 1 used for data treatment in accordance with a method embodying the present invention for producing a high resolution, high penetration, and high directivity marine seismic stratigraphic data.

Since the early 1970's numerous efforts have been made by the exploration industry to improve the resolution and accuracy of marine seismic data. Improvements have centred around controlled energy sources, digital recording and data processing. Instantaneous floating point recording and matching processing in high speed computers have substantially improved the reliability of reflection data and opened the door to more elaborate procedures such as migration and impedance displays, wavelet (pulse) processing, synthetic modeling and three-dimensional presentation. All of these processes were aimed at improving the range of usefulness of the final resulting data. This has enhanced "stratigraphic" detailing and reservoir engineering as checked by frequently using well-logging data as an input to the processing. However, earlier supposed breakthroughs that in some cases later turned out to be disappointments, such as "Bright Spot", have taught the industry against depending on various computer techniques based on inadequate data.

Referring now to the drawings and first to Figure 1, a marine seismic vessel 10 is shown on the surface 12 of a body of water, normally the sea. An energy source 14 is towed by the vessel 10 for transmitting a pulse downwardly into the water. The source 14 may either be towed on or below the surface 12.

A preferred energy source is the Fairflax (Trade Mark) minisleeve exploder system of Fairfield Industries Inc. Such a source provides an energy pulse length of less than one-millisecond positive pressure and produces a nearly perfect acoustic pulse wavelet having a finite period of less than three milliseconds and a broad frequency spectrum with a maximum at about 200-250 Hz, and an amplitude gradually decreasing above and below the maximum for about three octaves. The source is sleeve-contained and is held at a shallow towing depth of about two-thirds of a metre below the surface by a float system. The downward travelling energy pulse is largely ghost free and substantially free of ringing.

Although such a source pulse is preferred, it should be noted that the system embodying the invention hereinafter described is fully operable with a less than perfect source. Preferably, it is desirable that the acoustic pulse is of finite length in the time domain and has a relatively smooth frequency spectrum over a somewhat broad range, viz., in excess of one and one-half octaves.

As towed by the vessel is a cable streamer 16 along which are located a plurality of hydrophone arrays or detectors, 18a, 18b, ..., 18x. The cable

streamer is slanted downwardly from the end attached to the vessel to the free end thereof at a constant slope angle which, as shown, is preferably approximately 1.75 degrees.

Preferably the cable is made of clear plastic polyvinyl or polyurethane tubing of about 3.8 cm (1-1/2 inches) outer diameter. Twenty-four channels, each comprising 32 acceleration cancelling hydrophones arranged over 12.5 metres in a binomial tapered array, are evenly located at regular intervals along an entire 1200 metre cable length. Hence, the centre of each channel detector is spaced 50 metres from the centre of the adjacent detector arrays. Such a streamer is naturally buoyant, even with the inclusion of or suspension of the hydrophone arrays therefrom. Therefore, it is necessary also to provide weights distributed along the streamer to obtain the slanting required. In addition, self-operated depth controllers are employed at typically four evenly spaced locations along the streamer to correct for cable droop or rising. One such suitable controller is described in U.S. Patent No. 3,931,608, "Cable Depth Control Apparatus", Jimmy R. Cole, January 6, 1976.

The front detector is positioned at a location conveniently beneath the surface of the water so as to be free of surface turbulence, which means a depth of approximately 3 metres (10 feet). With the slope at about 1.75 degrees, the twenty-four detector is positioned at a depth of approximately 38 metres (125 feet).

Figure 1 is also useful for explaining the phenomenon of primary and ghost reflections, at least with respect to the ideal geological and lithological structure illustrated. In this example structure, the bottom of the sea is located at a depth of 75 metres (250 feet) beneath the surface. This water/land bottom interface creates a first subsurface reflecting horizon or interface. Located an additional 225 metres (750 feet) beneath the bottom is a second reflecting horizon or interface. Located an additional 300 metres (1000 feet) beneath the second interface is a third reflecting horizon or interface. Finally, for purposes of discussion, a fourth reflecting horizon or interface is located another 900 metres (3000 feet) beneath the third interface.

Thus as shown in Figure 1, a first source pulse may be reflected off the reflecting interface 22 to be detected as a primary reflection pulse in detector 18a. The corresponding ghost reflection pulse, that is the ghost reflection pulse reaching the detector 18a is produced by a source pulse slightly in front of the first source pulse being reflected from interface 22 and then surface interface 12 to be detected as a ghost reflection pulse in detector 18a. Similar primary and ghost reflections are received from interface 22 at each of the successive detectors 18b to 18x along cable 16.

For each of the seismic reflecting interfaces, namely, interfaces 26, 28 and 30, a primary reflection pulse and a ghost reflection pulse is received by each detector. For convenience, the primary and ghost reflection pulses to detector 18x are illustrated in Figure 1. The primary reflection pulse is formed from a source pulse following a path 32 from source 14, which path is reflected slightly at interface 28

before reflection off interface 30. The reflected pulse is then refracted at each interface 28, 26 and 22 and finally detected at detector 18x. The corresponding ghost reflection pulse is produced by a source pulse following a path 34 which is ahead of the path 32 and of course longer than the path 32 as it includes a segment following a reflection off interface 12.

It should also be noted that the strata between the interfaces may have, for purpose of discussion, a different velocity characteristic with respect to an acoustic pulse or wave. The representative velocity for the water strata is 1525 metres/sec (5000 feet/sec). For discussion purposes, the velocities of successively deeper strata are shown as 1615 metres/sec (5300 feet/sec), 1740 metres/sec (5700 feet/sec) and 2045 metres/sec (6700 feet/sec).

The cable slant is set to achieve an increase in the time domain between primary and ghost reflection pulses from one detector or hydrophone array to the next of two milliseconds. The particular slope illustrated of approximately 1.75 degrees is selected to optimally attenuate the ghost (or primary) reflection pulse in the frequency band of most interest (viz., 30-250 Hz). Other slopes for the cable are operable, however, and even preferred for other selected frequency bands. For a discussion of the factors involved in establishing a slope for achieving a good response from an evenly spaced linear array at a selectable frequency of operation, reference is made to *Electromagnetic Waves and Radiating Systems*, copyright 1950 by Prentice-Hall, Inc., Edward C. Jordan, pages 422-428.

As discussed above, the source pulse, although very short in time duration, has a broad range of frequencies preferably over about six octaves. Recorded through a 350 Hz anti-alias filter and digitally sampled in the time domain, the pulse appears as shown in Figure 3. The peaked frequency spectrum, on the other hand, appears as shown in Figure 2. It should be noted that the largest amplitude in the frequency spectrum is in the vicinity of about 200 Hz, the relative amplitude for adjacent frequencies decreasing gradually below and above the centred largest amplitude frequency.

A Fourier analysis of two opposite polarity pulses, which the primary and ghost reflection pulses are, results in a plurality of peaks over the approximate frequency range of the source with intervening notches, depending on how close together the two separate polarity pulses are to each other. Actually, over a larger frequency range, other peaks appear, but for the approximate frequency spectrum of interest, from 0-500 Hz, when the two pulses are within, for example, 4 milliseconds on each other, then only two peaks separated by a notch are produced. On the other hand, when the primary pulse of a first polarity and the ghost pulse of a second polarity are many milliseconds apart, as is the case with a deep reflecting interface as detected at a detector at the tail end of the cable, within the 0-500 Hz range there is a plurality of perhaps twenty-four peaks with intervening notches. Figures 4, 5 and 6 are example of the frequency spectrums produced at the first, second and third detectors or arrays, respectively.

Figure 7 is part of the diagram shown in Figure 8 enlarged to illustrate the typical trace display shown in Figures 8, 9 and 10. The top trace in each of the four trace events shown in a primary reflection pulse trace and the bottom trace in each of the four trace pairs is the corresponding ghost reflection pulse trace. The type of trace pattern illustrated in Figure 7 is a "variable area trace", wherein the area between the trace and a zero base line when the pulse is of one polarity is shaded solid and the area between the trace and the zero base line when the pulse is of the opposite polarity is not shaded. In the example, the primary reflection pulse trace of each pattern starts out in a positive polarity, so the first portion of such trace is shaded. The second portion of each primary reflection pulse trace is negative and, hence, unshaded.

Each of the corresponding ghost reflection pulse traces, on the other hand, starts out with a negative polarity and is unshaded as shown in Figure 7. The second portion of each ghost trace is however of positive polarity and hence shaded.

As shown in Figures 8, 9 and 10, however, only the shaded portion of each trace is visible. Hence, the spacing between the primary and ghost reflection pair is exaggerated in Figures 8 and 9 since only the first portion of the primary reflection pulse trace and the second portion of the ghost reflection pulse trace appear. As will be explained more fully below in Figure 10, the traces are phase reversed and hence the diagram shows the respective primary and ghost reflection pulse traces unduly close to one another. This may be understood by visualizing the unshaded portions of the traces in Figure 7, shaded and the originally shaded portions, unshaded.

Referring now to Figure 8, which represents a common depth point collection file, there are four patterns of pulse pairs shown in this time diagram, corresponding to reflection pulses produced from each interface 22, 26, 28 and 30. Each pulse pair represents a primary reflection pulse and a corresponding ghost reflection pulse. The top or first pattern represents the primary and ghost reflection pulses for interface 22 when those reflections are received at the respective twenty-four detectors. It should be noted that the times of arrival for the primary and ghost reflection pulses as received at a particular detector are very nearly the same. This is true for all twenty-four pairs. However, the pattern is relatively steep, indicating that the time taken for the reception of the primary and ghost reflection pulses to be received by the first detector is short compared with the time taken for the primary and ghost reflection pulses to be received at the twenty-fourth detector.

The second pattern is similar to the first, with two exceptions. First, the overall steepness of the trace pattern is not so great. This means that although it takes more time for the reflection pulse pairs to be received at detectors further from the source, the time difference between reception of pulses at the first and twenty-fourth detector is not so great for the reflections from interface 26 as for interface 22. Second, although the primary and ghost reflection pulses are relatively close together for the two

reflection pulses received at the first detector, the primary and ghost reflection pulses tend to become further spaced-apart in time as the distance of the detector from the source increases.

5 It will be seen that for interfaces 28 and 30, the patterns become progressively less steep, but the primary-to-ghost reflection pulses time spacing becomes progressively greater for the deeper interface reflections at the more distant detectors.

10 Now referring to Figure 9, the primary reflection pulse file is time aligned so that all of the primary reflection pulses for each of the detectors are time adjusted to the time of arrival of the reflection pulse at the first detector or array. The ghost reflection
15 pulses are correspondingly adjusted in time. However, as there is an original progressive spacing between the primary and ghost reflection pulses, this spacing progression is substantially maintained. It should be noted that the application of NMO
20 correction causes some change in the spacing.

The time alignments shown in Figure 9 are achieved in two steps. First, a static shift is applied to correct the time of arrival of the primary reflection
25 pulses to the time at which they would have arrived at a common datum plane, that is the water surface, by adding the vertical travel time from the water surface to the corresponding detector or array to each respective trace. Second, a normal moveout
(NMO) correction is applied based on a velocity
30 analysis conducted on the common depth point files after correction or "datumizing" of the primary reflection pulses, to the common datum plane.

Also, applying the normal moveout correction to achieve time alignment tends to stretch the indi-
35 vidual pulses. Since the most shallow interface trace pattern undergoes the greatest stretch, the pulses for those reflections that are time moved the most are also stretched the most. Therefore, there is a muting or dropping of data which has undergone a
40 great deal of pulse stretching. This is standard in practice for NMO corrections and does not have to be explained in greater detail. Different data manipulations determine where muting should occur on an individual judgement basis. However, it should be
45 noted that for the corrected patterns of Figures 9, only two reflection pairs have been retained for the top pattern, nine reflection pairs for the second pattern and eighteen pairs for the third pattern whereas all twenty-four pairs have been retained for
50 the fourth pattern.

In similar fashion, as shown in Figure 10, the ghost reflection pulses are respectively time aligned for each of the four patterns. However, two additional
55 adjustments are made thereto. First, the ghost reflection pulses (and therefore the primary reflection pulses as well) are phase reversed so to bring the ghost reflection pulses into phase with the primary reflection pulses of Figure 9. Next, the alignment of the ghost reflection pulses are raised in
60 time to correspond to the time of the primary reflection pulses of Figure 9 rather than to the time of arrival of the first ghost reflection pulse. Otherwise, this alignment is accomplished in a manner similar to that of aligning the primary reflection pulses.

65 Thus, a static shift is first applied to correct the ghost

reflection pulses to the common datum plane by subtracting the vertical travel time from the water surface to the detectors or arrays for each respective trace and then a normal moveout correction is
70 applied based on a velocity analysis conducted on the common depth point files after correction of the ghost reflection pulses to the common datum plane.

Referring now to Figure 11, there is shown the composite alignment of a time-aligned primary
75 reflection pulse pattern with a time-aligned ghost reflection pulse pattern, the time-aligning ghost reflection pulse pattern being time shifted to begin at the end of the time aligned primary reflection pulse pattern. As can be seen from Figure 11, in the area
80 where the primary reflection pulses are aligned, the ghost reflection pulses corresponding to these primary reflection pulses are misaligned so that each individual reflection pulse is offset in time from the others. Likewise, in the area where the ghost reflection
85 pulses are aligned, the primary reflection pulse pattern is such that the individual primary reflection pulses are misaligned or offset from each other.

Figure 12A shows the effective stacking of the primary reflection pulse pattern just described, Figure 12B shows the effective stacking of the ghost
90 reflection pulse pattern just described and Figure 12C shows the effective combined stacking, all the pulses being digitally sampled in a format suitable for computer processing. It may be noted that the result is an effective 48-fold stack of the meaningful
95 data, the stacking greatly enhancing or reinforcing the meaningful data without the use of artificial inverse filtering. In a sense, the composite stacking achieves effective gap filling of the frequency spectrum shown in Figures 4, 5 and 6, and the other
100 similar spectrum for the other detectors or arrays compensating for both amplitude and phase distortions. The misaligned and hence, non-building waveforms do not enhance or augment each other
105 and therefore are effectively discounted when compared with the 48-fold enhanced stack.

Figure 13 is a diagram illustrating the process of cancellation of a specific directed noise pulse pattern
40 out of the vertical plane. Such noise may occur, for example, from a totally foreign external source or may occur from a reflection of the source acoustic pulse from a surface at the side of the vertical plane
110 passing through the cable.

If it is assumed that the polarity of the noise pulse
40 is positive and the polarity of primary reflection pulse pattern 42 is positive, then the polarity of ghost reflection pulse pattern 44 is negative. When the primary reflection pulse pattern is time aligned, the ghost reflection pulse pattern is non-aligned and the
120 noise pulse pattern is non-aligned. This means that stacking of the primary reflection pulses will produce combined stacking signal wherein the primary reflection pulses are enhanced relative to reflection pulse and noise pulse patterns.

125 When the ghost reflection pulse pattern 44 is phase reversed and time aligned, as discussed above, the primary reflection pulse pattern is non-aligned and the noise pulse pattern is also non-aligned. It should be noted that aligning of the ghost
130 reflection pulse pattern requires a large amount of

time shifting than required for the primary reflection pulse pattern. The effect on the noise is that the noise pulse pattern is a little steeper than for the noise pulse pattern corresponding to the aligned primary reflection pulses. The two noise patterns are still not too far out of alignment but are phase reversed with respect to each other. Therefore, when the combined stack of ghost reflection pulses and primary reflection pulses is formed, there is a tendency toward noise cancellation, especially for noise at the lower frequencies. So, not only is the noise not enhanced in the stacking, but there is some cancellation. The net result is an enhanced directivity for desirable signals arriving approximately vertically.

Figures 14 and 15 are block diagrams illustrating one method embodying the invention for achieving step-by-step the results just described. The detected reflection pulses are digitally recorded on a magnetic tape recorder located on the vessel 10 as the pulse signals are received from the respective detectors or detector arrays located along the cable, as previously described. It can be assumed that uncorrected data is recorded on the recorder 50. In order to determine what NMO correcting factors are to be applied to the recorded data, it is first necessary to determine the RMS velocity of the average strata through which the reflection paths track. First, static corrections are applied to the raw data to correct the data to the common data or horizontal plane. This is done in static correction circuit 52 in conventional fashion. This connection is necessary because the cable is beneath the surface of the water and is at a slope. The primary static corrected curve under ideal conditions will tend to be hyperbolic. The absolute cable depth can be calculated from assumptions or actually measured.

There are three ways to measure the depth of the cable at a given location of a detector or an array. First, the cable can be provided with independently operated depth detectors at a number of the hydrophone detector locations. Such depth detectors yield useful direct measurements.

The second method of determining depth is from the data collected at the detector. This technique involves merely correlating a data window with respect to a phase reversal of the same data until the largest positive maximum occurs. The correlation lag time to this peak is the travel time of the ghost reflection pulse behind the primary reflection pulse, which is roughly the time of travel from the detector to the water surface and back again where the reflection energy propagates close to the vertical. This technique is most useful with respect to the deeper detectors toward the rear of the cable so long as the data pulses are still strong.

Third, the depth can be measured by the development of a frequency spectrum curve similar to that shown in Figures 4, 5 and 6. This may be done where the data is still clear enough to determine when a notch occurs and the number of peaks preceding that notch. For example, in Figure 4, the notch occurs at 250 Hz. The velocity of an acoustic pulse in salt water is about 1525 m/sec (5000 ft/sec). Therefore, the two-way travel to the first detector producing the

Figure 4 response is $1525 \div 250 = 6$ m ($5000 \div 250 = 20$ ft.). Hence, the first detector is located approximately 3 metres (10 feet) below the water surface.

In similar fashion, the location of the second detector can be determined from the response curve shown in Figure 5. If the first notch location is not clearly locatable but the second is, then the first may be more precisely located by the simple expedient of dividing by two. It should be noted that this technique is particularly useful for measurements where there is overlap of primary and ghost reflection pulses or for the detectors close to the end of the cable attached to the towing vessel 10.

Velocity analysis circuit 54 determines the velocity of the strata for use in NMO correction. Velocity determination is well-known in the art. One description is found in U.S. Patent 3,550,073, Foster, et al., and another is found in *Geophysics*, a publication of the Society of Exploration Geophysicists, Vol. 34, No. 6, published December, 1969, on page 859, in an article entitled "Velocity Spectra-Digital Computer Derivation and Applications of Velocity Functions", M. Turhan Taner and Fulton Koehler.

With the velocity information in hand, reference is now made to Figure 15 which is a block diagram of the components of the system of Figure 1 used for data treatment in accordance with a method embodying the present invention illustrating the sequence steps involved in that method.

The data acquisition step in the manner heretofore explained is concluded with the recording of the digital data records collated in recorder 50 by a digital field recorder 60. This raw data is prepared in typical fashion as the operator deems appropriate. These steps are accomplished by an edit, demultiplexer and gain recovery unit 62. The prepared data is then collected into CDP files in a sorter 64 for display in accordance with Figure 8. At this point, the data is treated twice, once for primary reflection enhancement and once for ghost reflection enhancement.

The static shift to correct the primary reflection pulses to the common datum plane is performed by static corrector 66. Velocity analysis is then performed on the corrected data, as explained in connection with Figure 14 by velocity analyzer 68, and the appropriate velocity function is selected for each CDP file to be input to NMO corrector 70. NMO corrector 70 applies NMO corrections to the data from static corrector 66 and the results are then muted in mute unit 72 to remove portions of the data where the operator determines that the NMO stretch was too large. The outputs from the mute unit are then summed for each CDP file and scaled in stack unit 74 so that the less muted files do not appear to be proportionally larger or more significant than the more muted files. If this were not done, stacking of two traces for the top file of Figure 9 would carry less significance than the stacking of the twenty-four traces for the bottom file of Figure 9.

The data from sorter 64 is also supplied to a ghost reflection pulse channel where it is phase reversed by phase reversal unit 80, the output of which is applied to static corrector 86 to correct the ghost reflection pulses to the common datum plane. The

ghost reflection pulse data is processed in units 88, 90, 92 and 94 in similar fashion to the processing performed in units 68, 70, 72 and 74 respectively or the primary reflection pulse data, as explained above.

The outputs from stack units 74 and 94 are added in a sum unit 96 to produce a combined stack. The operator may then, further treat the results in unit 100, which may include one or more filters, deconvolution processes, migrations and the like.

Thus, a system embodying the present invention allows an improvement in the collection of data and enables the improved processing thereof without artificial compensating filtering and amplification, for example notch filters are not required to connect for ghost reflections thereby producing a breakthrough in data quality and usefulness.

Further the present invention provides an improved high resolution marine seismic stratigraphic system that avoids, in the data handling portion of the system, the use of an inverse filter which, in gathering data and in its complementary treatment increases penetration with the same strength source as used in prior art systems by operating in such a manner to avoid amplifying noise. Hence, it is possible to achieve operation at a higher signal-to-noise ratio than that which was inherent in prior art systems.

Also, the present invention provides an improved focused or directed marine seismic stratigraphic system, which as an overall system of data collection and processing, attenuates noise directed at the arrays of detectors located along a cable or streamer other than from the vertical direction by 6 dB or more.

Thus, in the frequency domain, increasing the depth of individual traces in effect generates a controlled multi-element filter. After dual NMO correction and stacking, the notches related to trace depth disappear, producing a nearly perfect flattened response which is ideal for full spectral recovery. Aside from substantial increases in the signal-to-noise ratio associated with the double stack, at least two other favourable effects are observed.

First, as the cable or streamer is towed further beneath the water system than in the prior art systems, the cable or streamer detectors are moved away from the noise created at the water surface thus permitting operations to continue under more adverse weather conditions than was possible with the prior art systems.

Second, phase reversal and double stacking suppress source-generated reflection pulses and other noise at any depth out of the plane of the vertical profile. Even the pulses reflected from the deepest interface will have the benefits of this directive lateral filter with attendant increases in clarity and resolution. The combined effects of the system just described is expected to provide data signal improvement in the order of 12-18 dB and provide 5-8 milliseconds resolution, with a resulting extremely accurate response to depths as deep as 3000 m (10,000 feet) in many areas offshore.

It may also be noted that the greatest enhance-

ment of data is for the pulses reflected from the deep interfaces. Therefore, it is anticipated that the method embodying the present invention may be employed in association with prior art systems

employing inverse filtering for the shallower reflections where the resolution is already satisfactory. A system embodying the present invention is most advantageously employed for data collection and processing with regard to reflections from the greater depths.

The order of the steps in the Figure 15 is not critical provided that the end results are the same, as illustrated and described hereinabove. Also, certain steps in the primary and ghost channels can be combined, although it should be noted that the static corrections and the velocity functions will be different for a corresponding primary and ghost reflection pulse pair.

Also, beneficial results may be achieved using a lower frequency (e.g. 10-125 Hz) conventional source than the source discussed above. For example, air guns or water guns can be used for any energy source and a longer cable having more detectors can be used as the streamer. Also, the cable may be sloped at a slightly greater or smaller angle to the water surface or may be reversed sloped or even arranged in a "V" configuration or an inverted "V" configuration, if desired. (It should be apparent that either of these latter two configurations could place two detectors at the same level below the water surface, but that such configuration would still be quite operable). Higher frequency sources than that discussed above could also be employed, if desired.

Although the system of stacking the data hereinabove described is preferably a combined stack of the aligned primary reflection pulse data with the aligned ghost reflection pulse data, superior results over the prior art are achieved using only a primary reflection pulse data stack or a ghost reflection pulse data stack. In some cases where the data processing cost factors are quite important or where the data is satisfactorily strong, these or other such considerations may determine that the preferred operation of the system is with less than full combined stacking.

CLAIMS

1. A system for collecting and processing seismic data comprising: a movable seismic source for introducing an acoustic pulse into a body of water covering part of the Earth's surface; detecting means movable synchronously with the source by towing means and comprising a cable arranged below the water surface at an angle thereto having a plurality of detectors spaced along the length thereof, each of the detectors being provided to detect both primary and ghost reflection pulses produced by reflection of the source pulse from a reflection interface or interfaces at or within the part of the Earth's surface substantially beneath the body of water; and primary reflection pulse correction means for time-aligning the primary reflection pulses and stacking the time-aligning pulses to emphasize the primary reflection pulses with respect to the ghost reflection pulses.

2. A system according to claim 1, wherein the primary reflection pulse connection means includes muting and sealing means to provide stacked pulses which are substantially free of pulse stretch distortion and are proportionally sized with respect to one another.

3. A system according to claim 1 or 2, including ghost-reflection pulse correction means for reversing the phase of the ghost reflection pulses, time-aligning the phase-reversed ghost reflection pulses and stacking the time-aligned phase-reversed ghost reflection pulses to enhance the ghost reflection pulses with respect to the primary reflection pulses.

4. A system according to claim 3, wherein the ghost reflection pulse correction means includes muting and sealing means to provide stacked pulses which are substantially free of pulse stretch distortion and are proportionally sized with respect to one another.

5. A system according to claim 3 or 4, wherein the ghost reflection pulse correction means includes data shift means for positioning the phase-reversed and time-aligned ghost reflection pulses for alignment with the time-aligned primary reflection pulses.

6. A system according to claim 3, 4 or 5, wherein the ghost reflection pulse correction means includes time delay means for serially aligning the phase-reversed and time-aligned ghost reflection pulses with the time-aligned primary reflection pulses.

7. A system according to any one of claim 3 to 6, including combining means for stacking the output of the primary reflection pulse correction means with the output of the ghost reflection pulse correction means.

8. A system according to any preceding claim, wherein the source acoustic pulse has a period of less than approximately three milliseconds.

9. A system according to any preceding claim wherein the source acoustic pulse has a maximum amplitude in the frequency domain at approximately 200 Hz, the amplitude gradually decreasing for about three octaves above and below the maximum amplitude.

10. A system according to any preceding claim wherein the source pulse has a frequency spectrum lying substantially between approximately 0 and 500 Hz.

11. A system according to any preceding claim, wherein the detector closest to an end of the cable attached to the towing means is at a depth of about 3 metres below the water surface.

12. A system according to any preceding claim, wherein each detector comprises a hydrophone array.

13. A system according to claim 12, wherein 24 hydrophone arrays are provided along the length of the cable.

14. A system according to claim 13, wherein the 24 hydrophone arrays are spaced at 25 metre intervals along the cable.

15. A system according to claim 13, wherein the 24 hydrophone arrays are spaced at 50 metre intervals along the cable.

16. A system according to any one of claims 12

to 15, wherein each hydrophone array comprises 32 hydrophones arranged over 12.5 metres in a binomial tapered array.

17. A system according to any one of claims 12 to 16, wherein the hydrophone arrays each comprise acceleration cancelling hydrophones.

18. A system according to any preceding claim, wherein the cable is arranged below the water surface at an angle thereto such that a time difference between the arrival of a primary reflection pulse and a ghost reflection pulse at one detector is increased by approximately two milliseconds with respect to the time difference between arrivals at the adjacent detector closer to the towing means.

19. A system according to any preceding claim, wherein the cable lies below the water surface at an angle of approximately 1.75 degrees thereto.

20. A method for collecting and processing seismic data, comprising: introducing an acoustic pulse having a broad frequency spectrum into a body of water covering part of the Earth's surface; detecting the primary and ghost reflection pulses reflected from a reflection interfaces at or within the part of the Earth's surface substantially beneath the body of water at a plurality of detector locations, the first detector location being sufficiently beneath the surface of the water to be substantially free of surface interference and successive detector locations being positioned increasingly deeper beneath the water surface; time-aligning the detected primary reflection pulses; and stacking the time-aligned detected reflection pulses to emphasize the primary reflection pulses with respect to the ghost reflection pulses.

21. A method according to claim 20 and further comprising: phase-reversing the ghost reflection pulses; time-aligning the phase-reversed ghost reflection pulses, and stacking the time-aligned ghost reflection pulses to enhance the ghost reflection pulses with respect to the primary reflection pulses.

22. A method according to claim 21 and further comprising combining the stacked time-aligned primary and ghost reflection pulses.

23. A method according to claim 22, including shifting the time-aligned ghost reflection pulses to correspond with the time-aligned primary reflection pulses before combining the time-aligned primary and ghost reflection pulses.

24. A method according to claim 23, including time delaying the shifted time-aligned ghost reflection pulses to immediately follow the time-aligned primary reflection pulses prior to combining the time-aligned primary and ghost reflection pulses.

25. A system for collecting and processing seismic data substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

26. A method for collecting and processing seismic data substantially as hereinbefore described with reference to the accompanying drawings.

27. Any novel feature or combination of features herein disclosed.